

Percussive Excavation of Lunar Soil

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Abstract. *It has been suggested using a percussive motion could improve the efficiency of excavation by up to 90%. If this is proven to be true it would be very beneficial to excavation projects on the Moon and Mars. The purpose of this study is to design, build and test a percussive tool which could dig a trench and then compare this data against that of a non-percussive tool of the same shape and size. The results of this test thus far have been inconclusive due to malfunctions in the testbed and percussive bucket; however, experimental results from small scale experiments confirm this higher efficiency and support further testing.*

I. Introduction

On our journey back to the moon with the constellation project there will be a need to move an exuberant amount of lunar surface, more commonly referred to as regolith, to construct a permanent outpost. On the initial missions back to the moon the first projects in the construction of this outpost will be to dig ditches for cables, construct roads and landing pads, and constructing berms around the launch pads. As the outpost becomes more developed with personal staying longer durations of time, there will be a shift in the excavation requirements from outpost construction to oxygen production.

The properties of lunar soil along with the moons reduced gravity make the task of excavating very difficult. The lunar soil is very dense and has a high cohesion rate. When you look at the soil particles under a microscope it is seen that the smaller particles have a large surface area compared to their volume, this allows more surface contact where the cohesive properties act. Whereas, the larger particles also have a large surface area, they have many more ridged edges and surface imperfections causing them to bind together. When the particle sizes are put together, the cohesion rate becomes very high. The soil can also become very compacted; this causes a lot of the soil to get compressed together and the cohesive property will make the soil stay that compacted. These properties make any effort to dig on the moon problematic; additionally, the moon's gravitational force is approximately one sixth that of Earth. This means that the traction of any vehicle on the lunar surface will be greatly reduced; this diminishes the usefulness of plow and bulldozer type excavators. This is because these excavation vehicles rely heavily on their increased weight to hold them to the ground and reduce chances of slip while they are moving soil. Adding additional mass to account for the reduced gravity is not an option because in order to make the journey to the moon these tools need to be as light as possible to be launched into space.

It has been suggested that a digging tool which have a percussion motion can reduce the forces required to penetrate the soil and excavate. A simple association that can be made to adding percussion is jerking a shovel as it is inserted into soil. It is discussed in Ref. 1 that this reduction can be as great as 90% under optimized conditions. "Experimental results showed 71 to 93% draft force reductions while applying vibratory motion in the longitudinal direction"¹. Here it is discussed that adding percussion to a tool in the direction of the dig can dramatically decrease the required forces. Other factors that affect the percentage of force reduction are the amplitude and frequency of percussion and the soil condition. "The significant force reduction factors suggest that the vibrating blade reduces soil strength by decreasing cohesiveness and effective stress for dry to ductile soils."¹. Here it is suggested that the percussive forces decrease the soil binding properties and allow the soil to have more of a fluid motion, so that it will flow into the excavating tool. If the optimal frequency, amplitude, and direction are used on a percussive excavation tool which was able to greatly reduce the forces required to excavate than excavation vehicles would not have to rely on traction as much. This would be greatly beneficial because relying exclusively on traction is extremely inefficient due to power losses. As it was previously state we can not rely on traction as a source to

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produce a pushing force the way that they do for Earth excavation. Additionally, there are many problems with using traction as opposed to vibration assisted excavation, such as larger compaction on soil under the excavating vehicle. Overall, the efficiency of a vibratory assisted excavating tool is much higher than that of an excavating tool which relies on other sources, such as traction, to produce the required digging forces.

II. Testbed and Procedures

All of the testing has been performed on JSC-1a, which is a lunar soil simulant. There are other lunar simulants available; they are not available in the quantity that is needed for our experimental testbed. JSC-1a has many of the same characteristics as lunar soil. It has very small particle sizes, down to the sub-micrometer, and a high cohesion rate. However, there are differences in some of the properties such as a lower specific gravity, angle of internal friction, and a much higher elongation. This has people debating whether using JSC-1a as a simulant is the most accurate model we could be using. This is why newer lunar simulants, which more accurately represent what will be encountered on the moon, are being created and tested. However, since these new simulants are just coming out there are only small quantities available and they are very costly, so it would not have been practical to purchase the two tons that were required for the testbed used in these experiments.

A. Proof of Concept

In order to prove that percussive excavation can work, I conducted a small scale experiment to verify the concept. This experiment consisted of measuring the forces required to insert a spaded-hand shovel into a bucket of lunar stimulant. I removed the handle from the spaded-hand shovel and then used the spade as a bit in a rotary hammer drill. I would then drive the spade into a bucket of JSC-1a which was on top of a scale. I would push the rotary hammer drill to insert the spade into the regolith attempted to keep the force a constant value until it reached a depth of 6 inches. I did this for both non-percussive tests and percussive tests; a picture of the testing setup can be seen in Img. 1. Then I would record the force and time that it required to get to this depth. Since the force required to penetrate the soil is related to the compaction of the regolith I attempted to keep this value constant by shaking the bucket for a constant rate between each test so that the regolith would become reset. I collected a series of data points then plotted these points on a graph which can be seen in Fig. 1. From this graph it can be said that there is a weak relation between the time and force required to get to a specified depth. To account for this in my later experiments, I was able to use a constant velocity to move through the regolith, which would cancel out any biased data. The average non-percussive force, $F_{\text{AVG_Non-Percussive}}$, required to get to a depth of 6 inches was approximately 93.33 lbs, whereas, the average percussive force, $F_{\text{AVG_Percussive}}$, to get to this same depth was 15.76 lbs. Using Eq. 1, I obtained that there is an 83% reduction in force required to push to the 6 inch depth. While this is not the 90% reduction that was mentioned in Ref 1, it is still very close. However, it is mentioned in Ref. 1 that “mathematical models for vibratory tools predicted draft reductions above 90% for optimized operating parameters, significantly exceeding experimental results.” This could be due to unreasonable assumptions made in the mathematical models or because unaccounted for surface frictions and a greater point resistance at the point of penetration.



Image 1. The proof of concept experiment

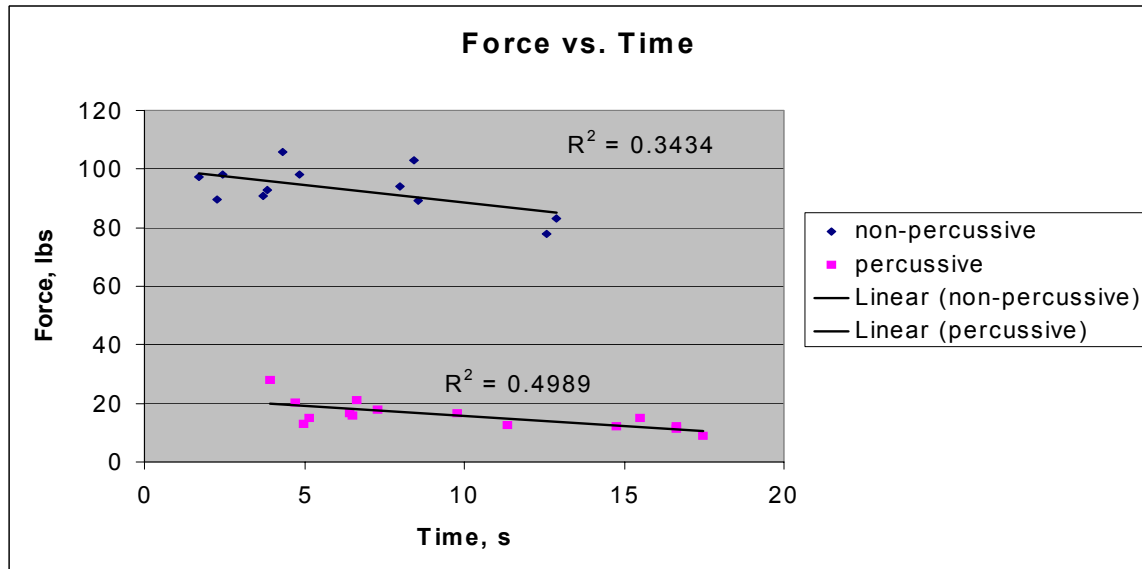


Figure 1. Force vs. Time graph for the data collected from the “Proof of Concept” experiment

$$\% \text{ Force Reduction} = \left(1 - \frac{F_{AVG_Percussive}}{F_{AVG_Non-percussive}}\right) \times 100 \quad (1)$$

Overall, this experiment demonstrated that with the added percussive motion to the digging tool, the forces required to reach a specified depth were more easily obtained. This supports the concept behind percussive excavation, and also provides input into certain parameters that need to be addressed in later testing, such as velocity of the digging tool, and the level of compaction of the regolith

B. Testbed

The testbed that all of the larger scale tests were conducted in was constructed over the summer of 2008 by a group of four interns who were working on this project. They entitled the testbed the Regolith Simulant Containment and Analysis Box (RSCAB); however, it has become known as the “sandbox” for simplicity. A picture of this testbed can be seen in Im. 2. A cyclone can be seen inside of the sandbox, this is an important tool because it is used as a ventilation system. This is needed because when the regolith is being moved around a lot it creates a dust cloud in the air which takes a long time to settle. This



Image 2. RSCAB

cyclone sucks in the dusty air and filters out the simulant particles. This improves the visibility when a larger dust cloud is formed, in addition to lowering the potential hazard inside the sandbox. This hazard is due to the sub-micrometer sized particles in the air. If someone were to inhale these particles they would be too small for the body to filter naturally, thus allowing them to settle in the lungs permanently causing potential health risks. This is why anyone entering the sandbox must receive proper training and wear the proper personal protective equipment, such as a respirator and Tyvek suit. The hazards of this dust cloud are reduced for others in the room by a plastic covering over the entire sandbox which has zipper doorways for entering and exiting. These doorways are required to stay closed unless they are in the process of being used.

The sandbox also consists of 2 wooden boxes. Both have a capacity to hold 2.5 tons of lunar regolith, this is to allow all of the JSC-1a to be transported into one box and have another simulant used in the other box. The high box is where the simulant would be stored while not in use; whereas, the low box is what is used for testing. It can be seen that there is a rail system running on either side of this low box, with a bridge going across the low box along these rails.

This rail system has created some problems because there is an exceptionally large amount of friction taking place between the wheels on the bridge and the track. The wheels need to be perfectly aligned with no imperfections or else they will become jammed and stop rotating. One such jam can be seen in Im 3, here the top rail was not positioned correctly and the wheel became loose enough to bend off of its track. Figure 2 shows a graph of the force required to pull the bridge along the track with no regolith in the box. It is seen that the force required to pull the bridge is approximately 50 lbs; however, there are 2 locations on the graph where the force jumps to 90 – 100 lbs of force. When the track is inspected at these locations, it was seen that there were scratch marks on the metal tracks. This is because the bridge begins to torque and the bottom of the bridge will scrap the track if it hits an imperfection. I am presently looking into alternative methods to the wheel and track system in order to reduce friction and develop a system that is not as sensitive



Image 3. Track jam

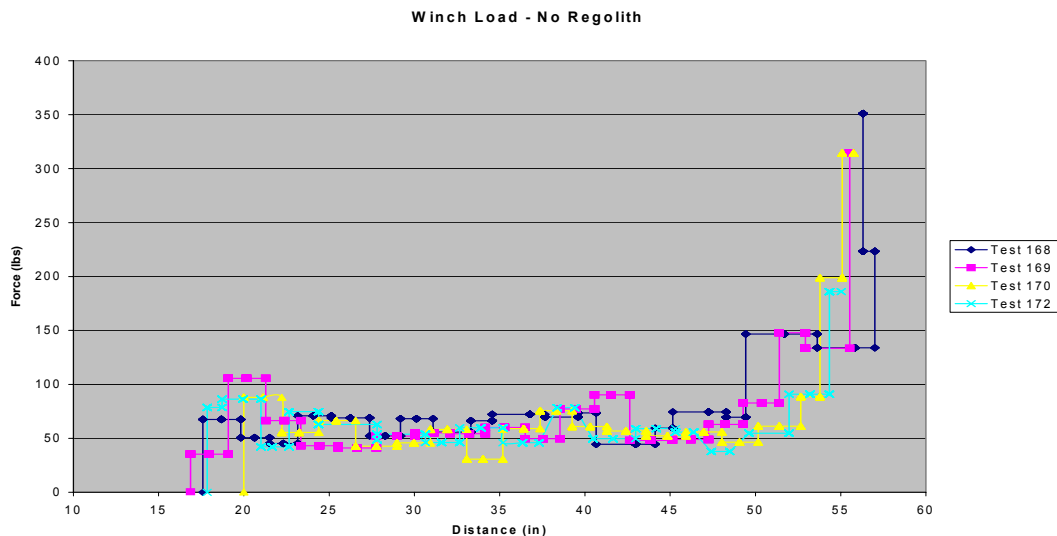


Figure 2. This graph shows the force required to move the bridge while the bucket was not digging any regolith. Effectively it shows just the mass moving and the friction in the system.

C. Bucket Design

The major requirements for the design of this excavation tool is that it had to dig a trench that was 100 meters long, 30 cm deep, and 10 cm wide at the bottom, with 70 ° inclined walls.

Backhoes and similar equipment offer a variety of soil manipulation capabilities. The hoe is ideally suited for ditch or trench excavation. Utilizing the two piece boom at angles close to ninety degrees, the backhoe operates most efficiently to scoop and move soil or flatten existing piles with the blade.²

Here it is stated that backhoes are the ideal tool for digging trenches. This makes sense because the “V” shaped bucket of a backhoe fulfills the shape that most trenches form. Since this design can be made to fit exactly to the requirements it was the most logical choice to make.



Image 4. The percussive bucket designed by the summer interns.

The summer interns designed and tested a percussive bucket; however, due to the limited time in their design and production the design had some imperfections. Some of the more notable problems were a weak voice coil to produce the percussion, and large area on the bottom of the bucket that would get stuck in the regolith. The voice coil was grossly underpowered for the percussion. In order to get a voice coil that would have supplied adequate power it would have required adding too much more mass and would have cost a lot more. The other problem with the design was that the way the voice coil was installed created approximately a 2 inch area under the percussing teeth which would prevent the bucket from traveling through the regolith. A picture of this bucket can be seen in Im. 4.

For my design of a percussive bucket I was recommended to stay away from a voice coil due to their lack of power, size, and weight. I had to look into other sources to produce the percussive motion, some possibilities were a spring which would compress and then knock the bucket forward when it uncompressed, or a bucket with a hinge near the middle to create a pivot point, and then knocking the back of the bucket to move it, or a cam system where a motor would spin and then it would hit a peg to move the system forward. After a few design reviews with my mentor and assistant mentor, we decided that due to the lack of time we did not have the machine shop available so I had to keep the design as simple as possible; to do this I redesigned a non-percussing bucket, which I used to get a baseline for data comparison, and used a hinge to create a pivot point. Since the system could experience very high forces I had to use load rated hinges, the best ones I could find were a set rated for 2000 lbs, and they would fit perfectly into the design. I then used the rotary hammer drill to power the percussive motion by hitting an angle bracket on the back of the bucket. This redesign can be seen in Im. 5.

While I did not get a chance to run the tests that I wanted on this bucket due to problems with the tracks, I was able to run some quick tests. The results of these tests were less than desirable. The vibrations of the rotary hammer drill percussing caused a greater vibration than actual percussion in the bucket. The vibrations had a frequency and amplitude which made the regolith in the bucket more compact than outside the bucket. This was the complete opposite effect than what we wanted; we will need to look into another form of percussion which will allow for adjustments in amplitude and frequency.

D. Data Acquisition

For these experiments I was gathering data from a Futek load cell which was attached to where the winch pulled the bridge. This load cell would provide the amount of force required to pull the system along the track, which can be said is the required force to pull an excavation tool through the regolith. Unfortunately, as previously stated, there was a lot of friction between the wheels on the bridge and the rails, which got included in the gathered data as required force. The assumption can be made though that since both a percussive and non-percussive buckets were



Image 5. Percussive Bucket Designed for this study.

tested on the same testbed that the friction would affect both equally and you can just look at the difference in required force.

The Futek load cells were analyzed using a file written in Labview. This Labview file used the scaling factors of the sensors to convert them directly to forces and displayed both the raw data and the scaled data on an Excel sheet. It also displayed the time in ms, distance in inches, and velocity on this sheet. From these data sheets I was able to make graphs of the force vs. time and force vs. distance. Since the original file I used did not have the laser range finder, for the distance measurement, installed on it, I had to use the force vs. time. However, I felt that the force vs. distance graphs would be a lot more accurate and descriptive because you can see exactly how far you have gone and how much force it took to get there. Also, if there is a problem with the track you can see where it occurred. This is why the file has been updated to gather this data also for future test runs

E. Test Procedure

Each test would start off with the testbed preparation. This meant that I would have to put on the proper personal protective equipment so that I could go inside the sandbox. Once inside, I would make sure that the bridge is pulled back as far as it will go to ensure there is enough distance for the bucket to travel for the test. Next, I would form a pile of regolith in front of the bucket. For the first set of tests I used loose soil, so it was just a mound of loose regolith in front of the bucket. However, I wanted to study the effects of different levels of compaction so I then did a set of tests compacted with a vibratory hand compactor. For this compaction I simply used the vibratory hand compactor on top of the loose soil pile and compacted it then added more regolith so that it was at the depth that I wanted. I was suggested to try compacting the soil in different layers, similar to how roadways are constructed. This meant that I would put down approximately a half inch of regolith, then compress it either by hand compression or walking on it to compress it by foot. Then I would add another layer of regolith and continue this process until the desired depth was reached. Once the regolith was set I could climb out of the sandbox, typically leaving the clean suit inside, in order to not contaminate the rest of the air in the lab. This would have been bad because there were other people working in the lab without respirators on, and it could have been hazardous if too much regolith got in the air.

The rest of the setup was relatively easy compared to the regolith setting. I would make sure that the Labview file was all setup to collect data, and then once the file was turned on, I would calibrate the system and use the controls on the winch to pull the bucket. If I were using a percussive system I would turn the percussion on right before I used the winch to pull the bridge into the sandbox. I would stop the winch when the bucket would either travel to the end of the testbed, and would be full, or if the bridge would begin to torque and stop moving prior to the end of a run. This would happen if there was a problem with the track, or if the level of compaction in the bucket was too high. After the test was complete, I would need to climb back into the sandbox, put the clean suit back on, and then pull the bucket and bridge assembly out of the pile of regolith and measure the distance and depth of the dig. Then I would repeat the process of setting the soil and testing again.

III. Results and Conclusion

A. Non-Percussive Testing

The initial testing that I performed were on a non-percussive bucket, this way I can see what the loads would be on a bucket without the percussion assistance. This would provide a baseline for exactly how much the percussion assisted with reducing the digging forces. The non-percussive bucket was the same shape as the percussive buckets; however, there were no systems on it to implement percussion.

When I ran tests on the non-percussive bucket I had the soil compacted to different levels. These tests can be seen in the following graphs, Fig 3-7. From the graphs it is seen that there is not much difference between the loose soil, Fig 3, and the vibratory compaction, Fig 4. This is because the vibratory compacted soil was not compacted in layers, so it relied on the vibrations from the top of the pile to compact all the way down to the bottom. As it can be seen from the graphs, this is not the ideal way to compact soil. When you compact in layers, each new layer further compresses the previous layers allowing the particles to interlock even tighter. And as it is seen in the hand compacted soil in Fig. 5 and the foot compacted soil, Fig. 6, the level of compaction plays a large role in the force required to pull the bucket. This is why the foot compacted soil was the most difficult to pull the bucket through.

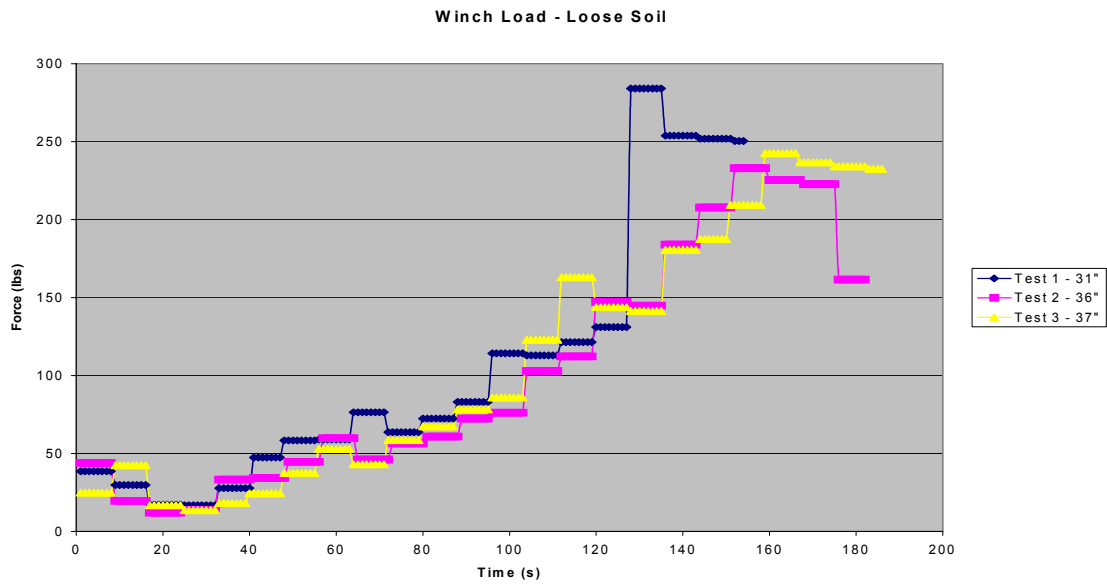


Figure 3. Non-percussive test in loose soil.

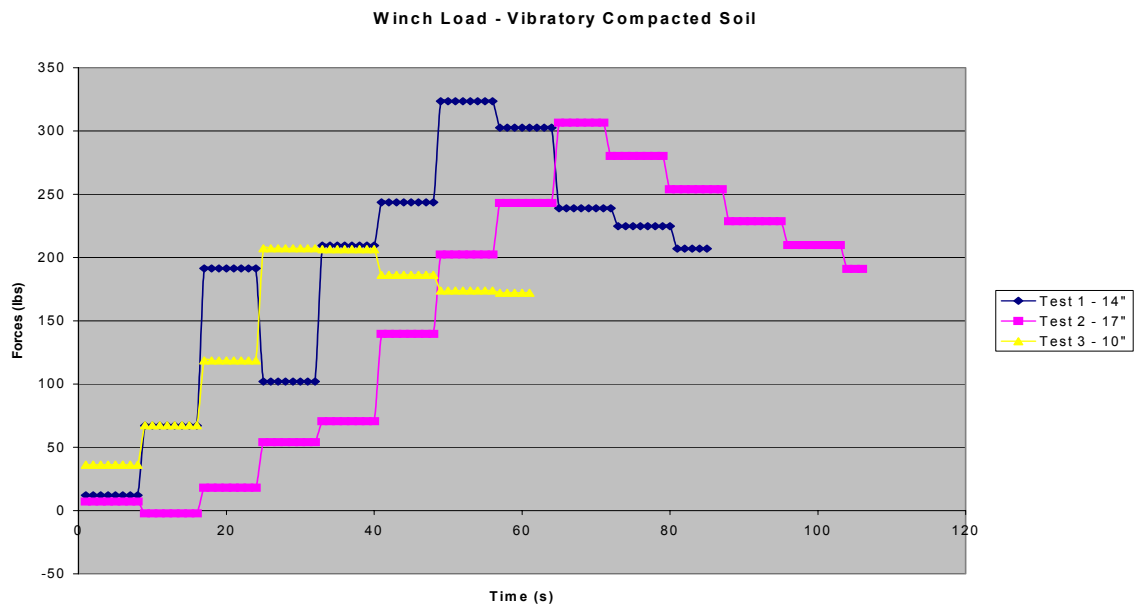


Figure 4. Non-percussive test in vibratory compressed soil.

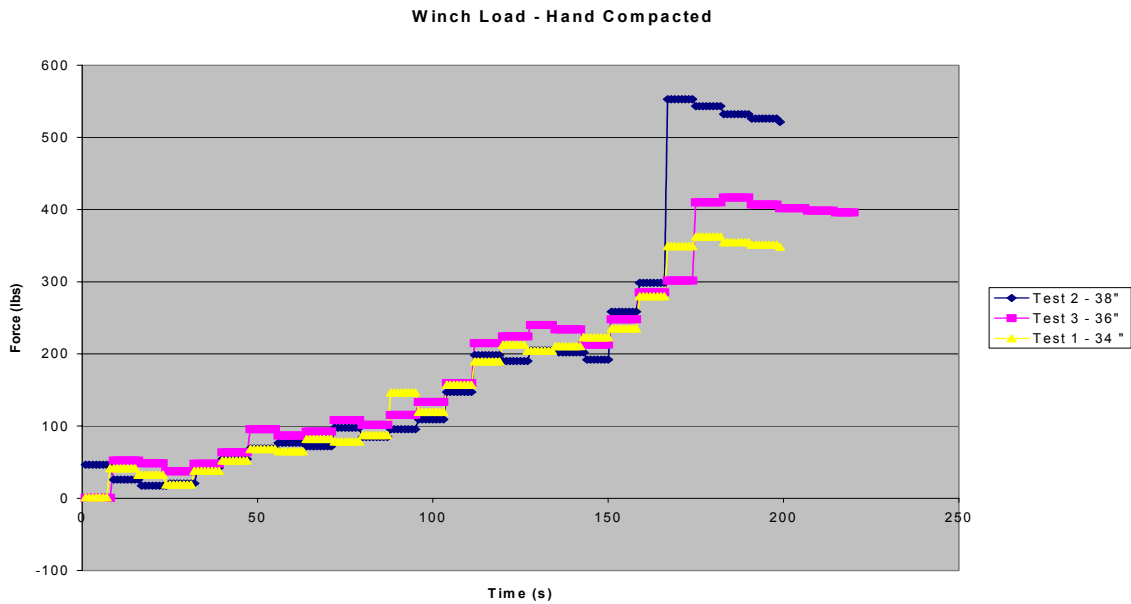


Figure 5. Non-percussive test in hand compacted soil.

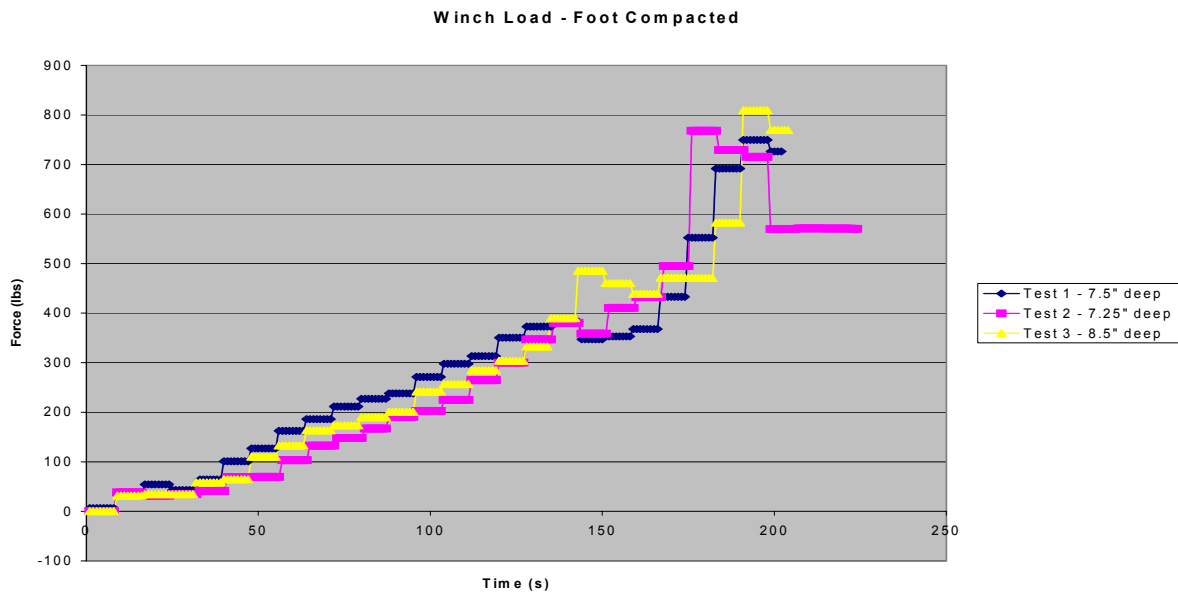


Figure 6. Non-percussive test in foot compacted soil.

Figure 7 shows the forces when a 0 degree angle of attack was used as opposed to an angle that was slightly less than 0 degrees, where the back of the bucket was down. The soil was foot compacted for these tests, so when it is compared directly with Fig 6 it can be seen that when the bucket is not angled it slightly reduced the forces

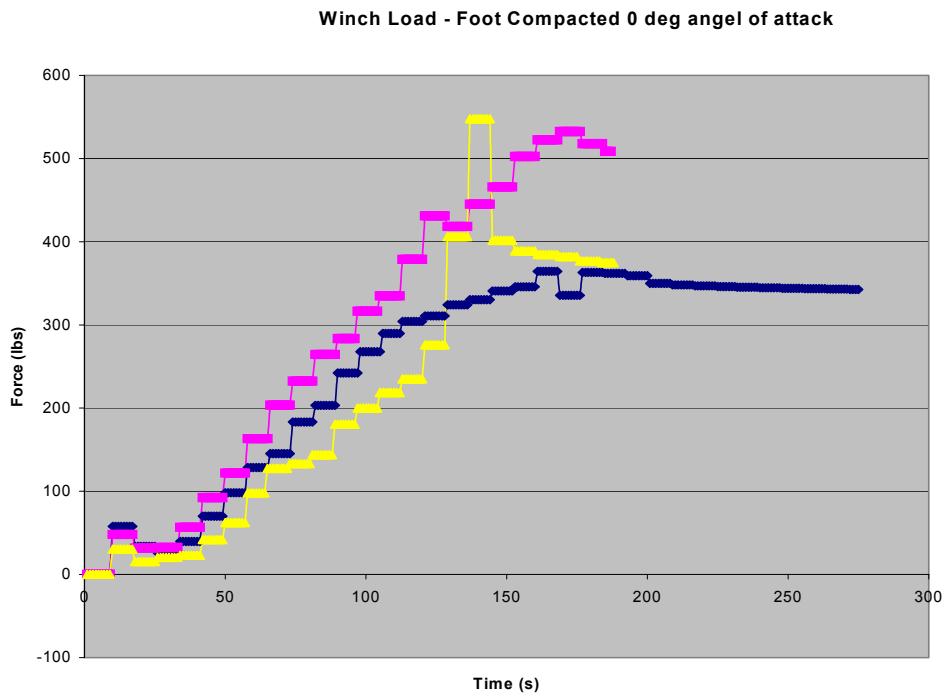


Figure 7. Non-percussive test in foot compacted soil with 0 degree angle of attack.

B. Percussive Bucket

The percussive bucket that I designed had to be quickly built and tested. However, testing was delayed due to a malfunction with the track system being used. In the few tests that were performed on the percussive bucket that I built the vibrations produced by the rotary hammer drill percussing compacted the soil as it entered the bucket. This was the complete opposite effect that was desired because we wanted the regolith to have more of a fluid motion into the bucket. If there were a way to dampen the vibrations or control the frequency and amplitude of the bucket the desired effect might be obtained. One other possibility to correct this problem might be to relocate the hinge which is supposed to allow the bucket to have a slight rotation and produce the percussing motion. Finally, more testing needs to be conducted, after the rail system is fixed, in order to determine if there truly is 90% more efficiency when using a percussive bucket.

Acknowledgments

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References

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